HRTES-X

High Resistivity TES micro-calorimeter :

a path toward breaking the power dissipation technological lock for future X-ray space telescopes

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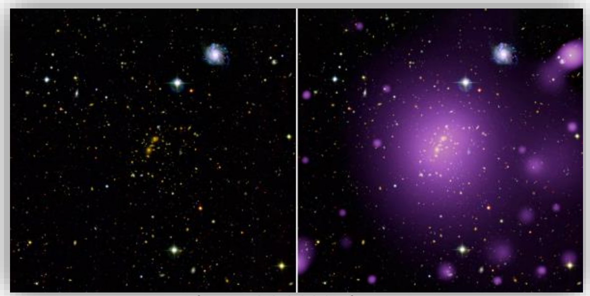
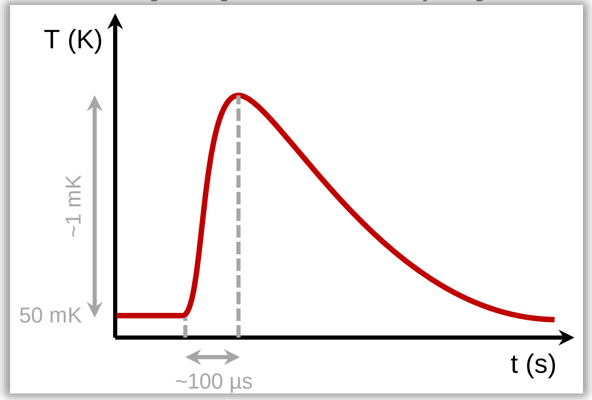
Introduction (1)

Context : Development of space spectro-imagers for X-ray astronomy

- Made of **matrices of micro-calorimeters**, working as follow :
  - An **absorber** is maintained at 50 mK by a weak thermal link.
  - When a X-photon arrives, its temperature increases (~mK), and then recovers its initial value.
  - The temperature increase is measured by a very sensitive **thermometer**, TES, which is a superconducting resistance maintained at its transition temperature ⇒ very high dR/dT.
  - The **resistance** increase is proportional to the **energy** of the incident **photon**.
- **Requirements :**
  - High **spectral resolution** ⇒ pixels with high **sensitivity** and low noise.
  - High **spatial resolution** and wide **field of view ⇒ large number of pixels.**
- Current technology is sensitive, but limited by a **technological lock :**
  - *Low* resistivity TES (10-100 mΩ) requires SQUID readout at same temperature ⇒ induces "**high" dissipation** at 50 mK.
  - But the **cooling power** of spatial cryo-coolers is very low : ~1 µW at 50 mK ⇒ this **limits** the **number of pixels : 4 000 max.**
- **Our goal :**
  - Make a reduced ***demonstrator*** prefiguring a space spectro-imager with **50 to 100 000 pixels**,
  - using a **new technology** for thermometers, the **HR-TES** (1-5 MΩ),
  - which allows to place the first stage of electronics at higher temperature (4 K) where power budget is much higher, and so allows much more pixels at 50 mK.



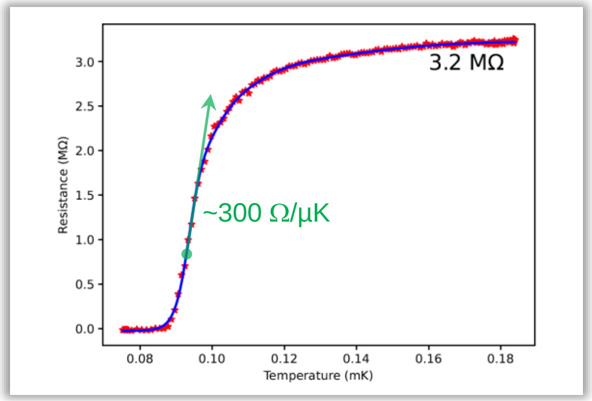
The XLSSC006 cluster : visible light image, X-ray image.



Micro-calorimeter signal shape.

High resistivity TES (HR-TES) technology

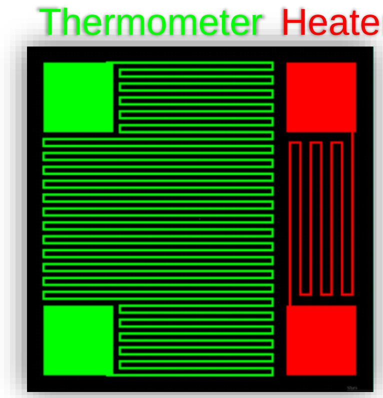
- Based on **NbSi** alloy, developed by IJCLab.
- **Advantages** : it offers
  - tunable **high** normal-state **resistance** ~3 MΩ ⇒ facilitates signal transport from 50 mK to 4 K ⇒ low consumption at 50 mK (< 20 pW/pixel) : < 1 µW for > 50 000 pixels,
  - *according simulations*, **high** energy **resolution** : ~2 eV for 500 µm pixels → state of the art.
- **Disadvantage :**
  High electron-phonon **decoupling** that until now reduced resolution.
  But we solve this problem thanks to an innovation : the **active** electro-thermal **feedback**.



R(T) characteristic of NbSi HR-TES thermometer.

Active electro-thermal feedback

- **Working principle**
  - An **heater** and a **thermometer** deposited on each pixel.
  - The electronic feedback makes heater continuously dissipate a weak Joule power.
  - When a photon arrives, this power is reduced by feedback
    ⇒ the **temperature** tends to **remain constant**.
  - So the **signal** is no more the temperature increase, but the **power decrease** in the heater.
- **Advantages**
  - The biasing current in the thermometer can be low and constant
    ⇒ reduces drastically the **electron-phonon thermal decoupling**
    ⇒ allows better electronic temperature restitution of the phonon temperature variations.
  - Excellent **stability**.
  - **Photon energy dynamic range** is increased.



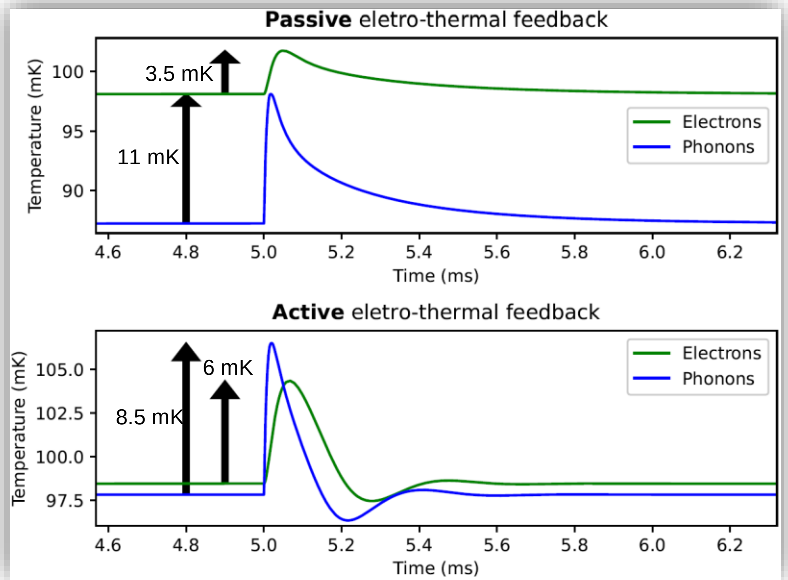
Design of a pixel : a 500 µm Si square with two NbSi meanders : one is a thermometer, the other an heater.

Development plan : 4 stages

- **WP1** : **Individual pixels** suspended by bonding wires.
  → *For quick tests and optimization.*
- **WP2** : **Mechanical matrices** of suspended membranes.
  → *To check the mechanical solidity.*
- **WP3** : **Sensitive matrices** of suspended membranes **equipped** by HR-TES.
  → *To obtain a reduced demonstrator.*
- **WP4** (in parallel) : Multiplexing **integrated circuit** and electronic boards.
  → *To prove the scalability to large matrices.*

Funding

- **P2IO** :
  - WP1, WP2, WP3 : 40 k€ → **detector manufacturing** by **IJCLab**
  - WP4 : 20 k€ → **electronics**, **cold tests** and setup by **IRFU**
- **Others** :
  - Thesis of **Benjamin Criton** (12/2020 – 12/2023) : about to start his 3rd year.
    Main author of this work.



Simulation of the same pixel working with passive (top) and active (bottom) feedback. In blue : phonons temperature (resulting from the incident photon energy deposition). In green : e^- temperature (inducing the electrical signal).

Modelling – simulation – optimization

Modelling

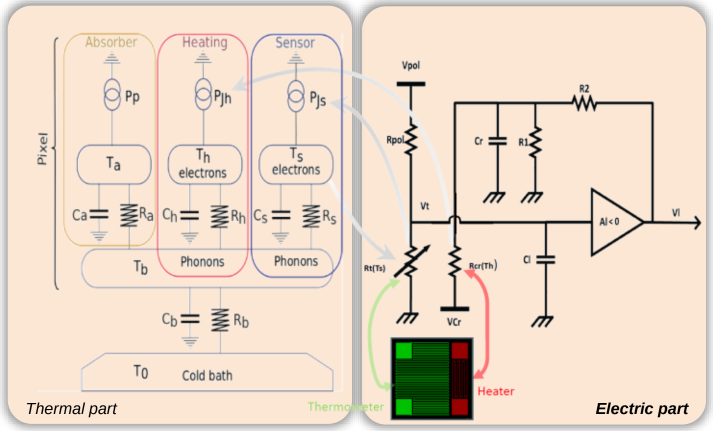
- Take into account the **thermal** part, the **electrical** part, and the **interactions** (by thermometer response and Joule dissipations).
- **Variables** :
  - **Temperatures** of absorber, pixel phonons, heating and thermometer electrons.
  - Electrical **voltages**.
- Simulation **parameters** :
  - **Thermal conductances** between absorber, thermometer, heater, cold bath.
  - **Thermal capacities** of absorber, thermometer, heater, substrate.
  - **Electrical** resistances and capacities.
  - **Noise sources**.

Simulation

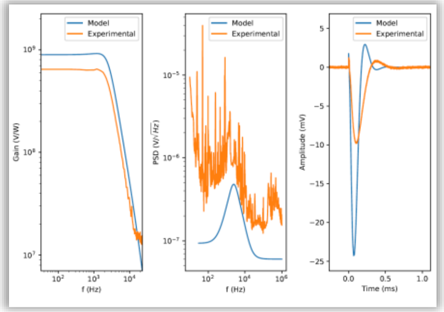
- Physical model implemented in two forms :
  - **Spice** simulator transient model → biasing, **signal shape**, saturation.
  - Linearized **analytical** model → noise spectra, **spectral resolution**.
- Validated by comparison between simulation and measurements : reasonable **agreement** ⇒ good confidence in simulation predictions.

Optimization

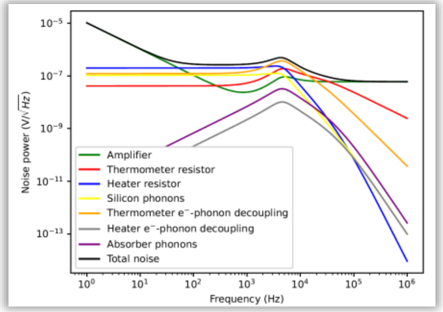
- Used to optimize the **dimensional parameters** to maximize the **spectral resolution**.
- Studied parameters : cold bath temperature, transition temperature, heater resistance and thermometer normal resistance.
- Results :
  - The most influential parameters are the **thermometer resistance** and the **transition temperature**.
  - When optimized the theoretical **spectral resolution** is lower than **2 eV**.
  - ⇒ **Used** to set the characteristics of the new individual pixel **prototypes** we manufactured.



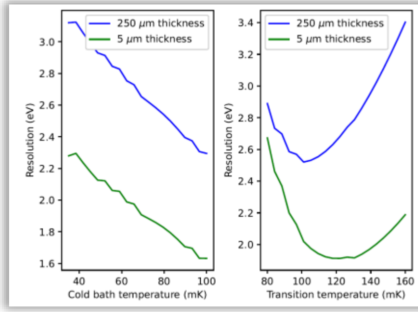
Electro-thermal model.



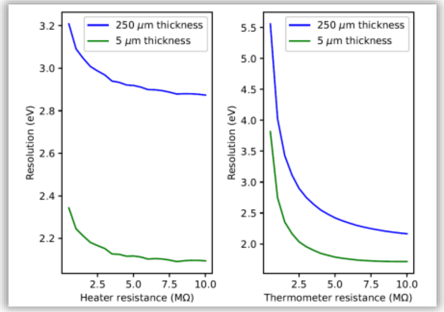
Comparison between model and experimental results.



Simulated noise PSD and its components.



Spectral resolution as a function of cold bath temperature (left) and transition temp. (right).



Spectral resolution as a function of heater (left) and thermometer (right) resistances.

New individual pixels (WP1)

Description

- Manufactured by IJCLab, implemented and tested by IRFU.
- On each 500 µm pixel : a **thermometer** (NbSi, Tc ≈ 130 mK),
  an **heater** (NbSi, without superconducting transition).
- **Suspended** and interconnected by **bonding wires** that adjust the thermal link resistance (2 Al → "no" thermal conduction, 2 Au → low thermal conduction).

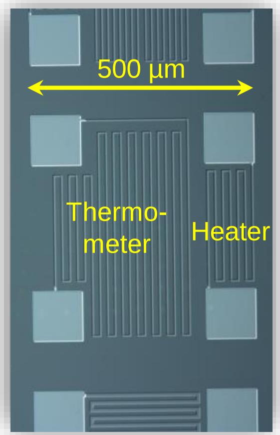
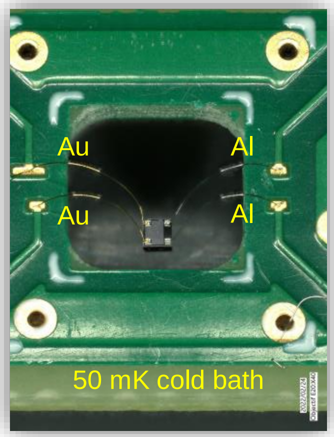


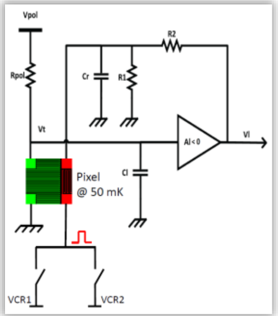
Photo of a pixel on its wafer, before cutting.



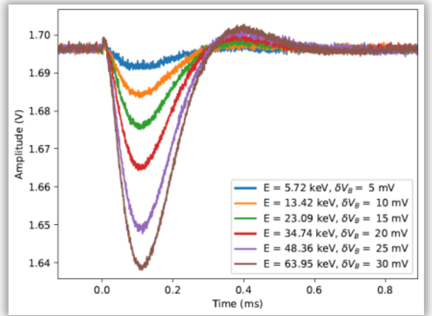
A pixel suspended by its Al and Au bonding wires.

Cold measurements

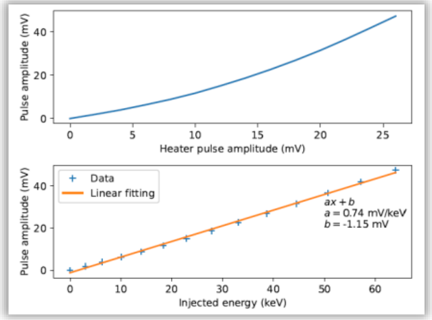
- Two types of stimuli :
  - **Heat pulse (Joule)** generated by on-chip **injection system**.
    ⇒ allows the energy calibration of the whole readout chain, the control of linearity, etc.
  - **X-photons** generated by ^{55}**Fe source**.



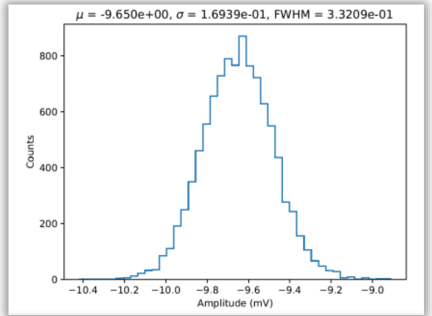
Schematic of heat pulse injection system.



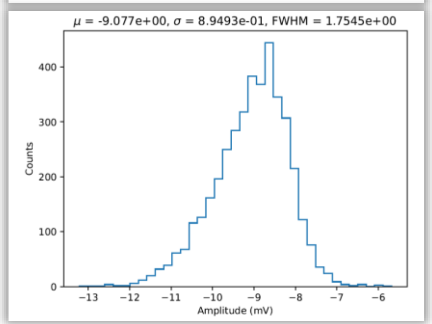
Output signal shape for heat pulses corresponding to various photons energies.



Output signal amplitude according to the heat pulse amplitudes (top) and to the corresponding injected energies.



Energy spectrum with heat injection system.



Energy spectrum with ^{55}Fe source.

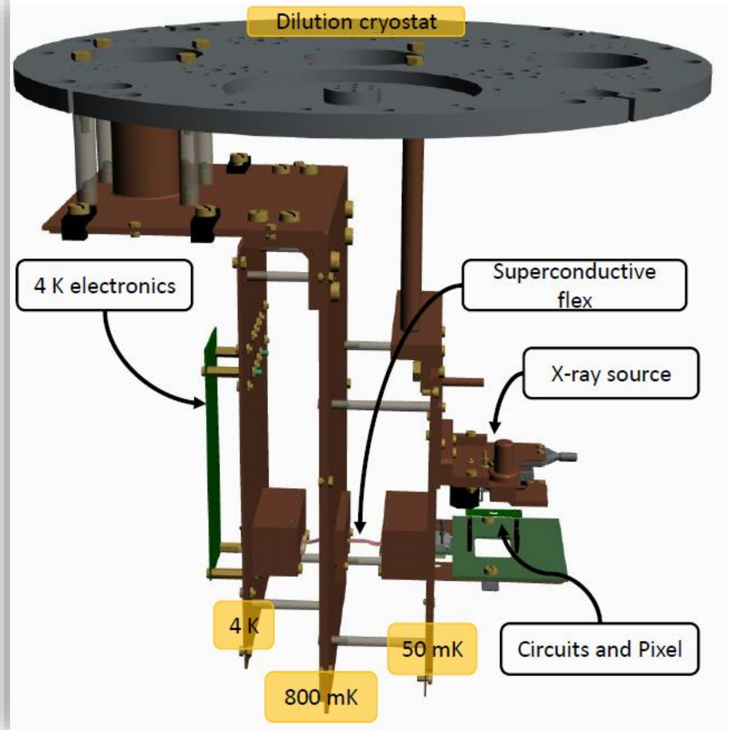
Conclusion

- Good **linearity** (⇒ constant voltage/energy gain : V/eV), good **stability**.
- Satisfactory **agreement** between simulation and measurements.
- But **bad energy resolution**, due to EM and vibration perturbations inducing **excess noises**
  ⇒ need to **improve** the test **setup**.

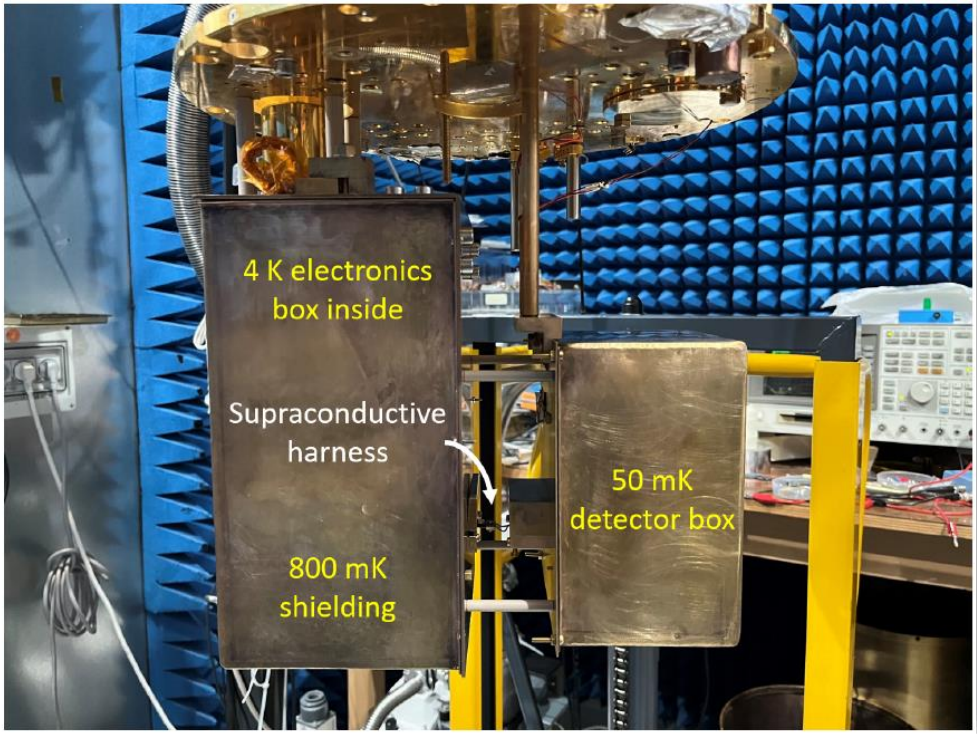
New experimental setup

- Two **functions** : **holding** and **cooling** of the chain elements.
- **Three temperature stages**, electrically interconnected by a shielded **superconductive harness** :
  - 50 mK : X-ray **source** (^{55}Fe), **detector**, **multiplexing electronics**.
  - 800 mK : Intermediate thermalization and IR screen.
  - 4 K : **amplification electronics**.
- Installation in progress.
- Expected **improvements** : better **EM** shielding, less **vibrations**.

37-tracks shielded superconductive harness.



3D drawing when EM and IR screen boxes are removed.



Photograph when the EM and IR screen boxes are closed.

Matrices (WP2 & WP3)

- Wire bonding technique cannot be used for matrices
  ⇒ use another technique : thin (5µm) **Si membranes suspended by beams**.
- Development in **two steps** :

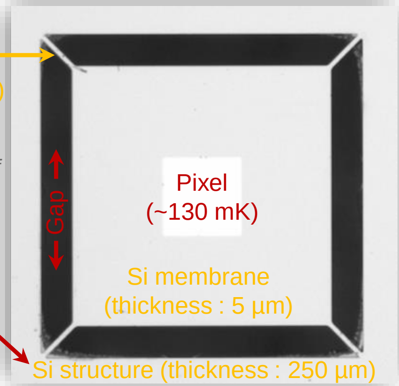
First step : mechanical matrices (WP2 : done)

- **Passive** matrices : no NbSi deposition on pixels ⇒ no thermometer nor heater.
- Aim : test **solidity** of membranes and implementation of **absorbers**.
- Two implementation means tested :
  - **Gluing** (→ about to be validated).
  - **Hybridization** by ball (→ very first tests performed, for the moment not successful).
- Conclusion : membrane and beam **solidity validated**.

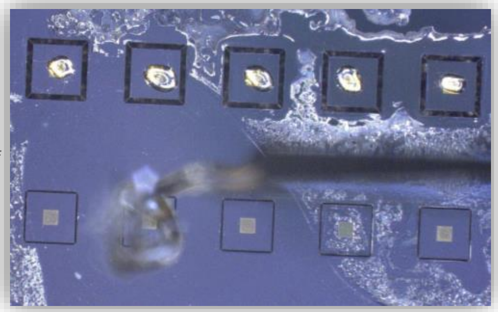
Second step : sensitive matrices (WP3 : in progress)

- 4x4 matrices with depositions of **HR-TES** (NbSi) on pixels
  and with **signal tracks** on beams and structure.
- A set of parameters will be tested :
  - different lengths, sections and quantities of beams
    (→ set of thermal resistances and mechanical solidities),
  - different thermometer resistances and track widths.

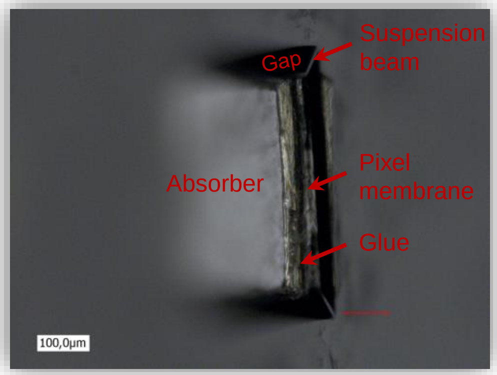
  Some matrices will be homogeneous, others heterogeneous (for comparison)
- Status : **design** in progress, manufacturing will start soon.



Photograph of one of the pixels of the mechanical matrix.



Deposition of glue on pixel membranes of mechanical matrix.



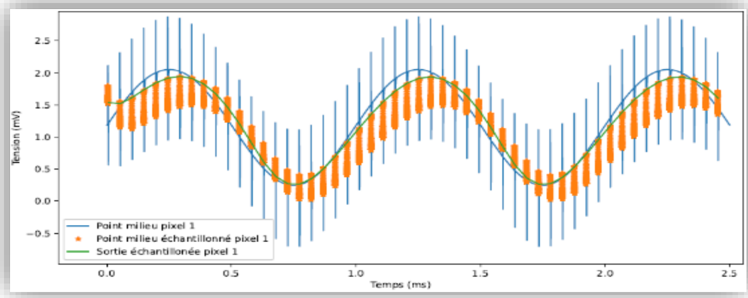
Side view of an absorber glued on a suspended pixel.

Electronics (WP4)

Designed to fit onto the cryo-cooler cooling power ⇒ functions split into **two stages** :

50 mK stage

- Function : **multiplexing** 16 → 1 of : 1) the readout signal **AND** 2) the feedback links.
- Requirements :
  - For **signal** : high impedance detector ⇒ anti-charge-injection system.
  - For **feedback** : holding between two updates when sampling ⇒ capacitive memory.
  - **Thermal budget** : consumption compatible with 1 µW for all channels 50 000 channels.
- Status :
  - **Integrated circuit** : **manufacturing** in progress, delivery in February 2023.
  - **Electronics boards** : **design** in progress.



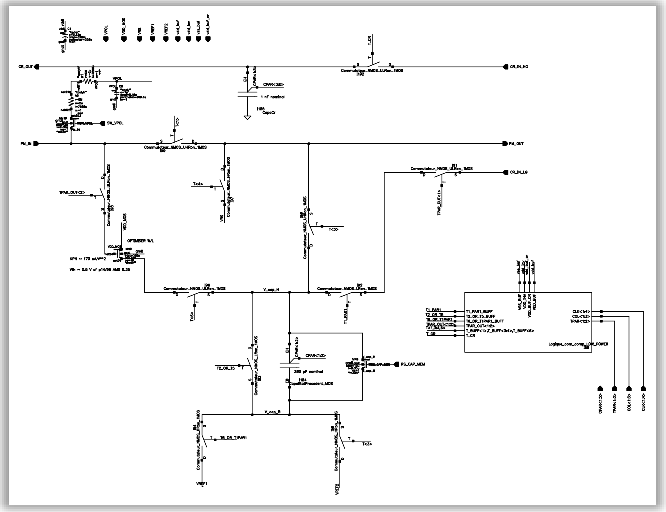
Simulation of an input signal (blue) and the resulting multiplexed output signal (green).

4 K stage

- Function : readout signal **amplification** and **feedback** signal generation.
- Requirements :
  low noise (1 nV/√Hz), high input impedance (→ HEMT), low dissipation.
- Status : development of a new version in progress.

Our goal

- Within one year**, connect** this **16 → 1 multiplexing electronics** to a **4x4 matrix** and **validate** the whole.



Schematic of the elementary cell multiplexing signal and feedback.

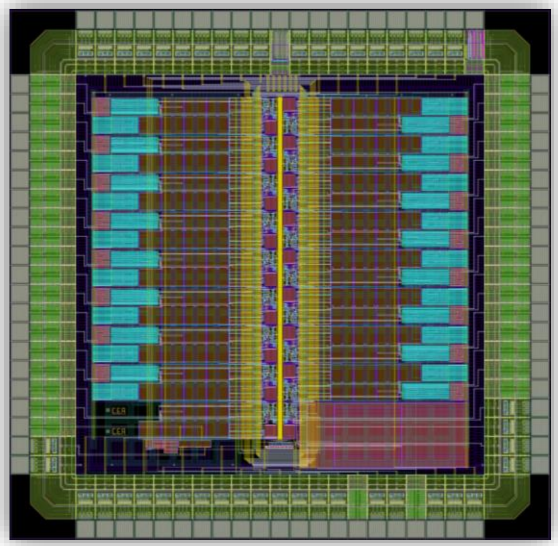


Image of the multiplexing integrated circuit.

Conclusion

The HR-TES promises :

- An **ultra-low power dissipation** readout at 50 mK, allowing matrices of more than **50 000 pixels** (→ today : 4000 max with LR-TES).
- A **spectral resolution** below **2 eV** (→ today : 2.5 eV with LR-TES), according to our detailed model and **theoretical simulations**.

We demonstrated today :

- The elimination of the effects of the **electron-phonon decoupling**, which was the blocking point of HR-TES use for X-ray, thanks to the **active electro-thermal feedback**.
- The strong **linearity** of the system, proved thanks to our **calibration device**.
- The effective **detection** of ^{55}Fe **X-ray photons** on 0.5 mm pixels.
- **But** : for the moment we obtain a **bad** experimental **spectral resolution**, due to high **parasitic noises** in the setup.

We are working on (→ *and should get within a year)* :

- The installation of our **new mechanical setup**
  → *should reduce the parasitic noises and improve the spectral resolution*.
- The design and manufacturing of **pixel-on-membrane matrices** (WP3 – IJCLab)
  → *should also improve the spectral resolution, and is an important step towards large matrices*.
- The design of the **new electronics boards** (50 mK and 4 k), implementing the **integrated circuit** that is in production (WP4)
  → *should prove the possibility of multiplexing the electro-thermal feedback*.

Future prospects

- A funding has been obtained to explore in parallel an **new improvement way** :
  - Transformation of the mechanical structure by **replacing** the **suspended membranes** by a **planar structure**, thanks to a technological innovation : a **thermally super-insulating multilayer structure**.
  - ⇒ this could transform the architecture of future low temperature detectors by facilitating their **manufacturing**, their implementation, and by improving their **robustness**.
- These developments are designed for X-ray spatial detection (beyond the Athena satellite project), but are **transposable** to other bands (sub-mm) and others contexts (ground instruments).

Comparison between present and expected future pixel architecture.